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LINERs and their Physical Mechanisms

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Abstract.

I review the basic properties of low-ionization nuclear emission-line regions (LINERs), as well as the main ionization mechanisms thus far proposed for them. There is substantial heterogeneity among LINERs, especially those with extended kpc-scale emission. An extensive survey by Ho, Filippenko, & Sargent quantifies with unprecedented accuracy the optical emission-line intensity ratios in the nuclei of a complete sample of 486 nearby, bright galaxies. Over 40% of all early-type galaxies in the sample can be classified as LINERs or LINER/H II transition objects. A nonstellar continuum is detected in many LINERs, suggesting that they are genuine AGNs powered by accretion onto a compact object. Broad H α emission similar to that of Seyfert 1 nuclei is seen in many LINERs. In some LINERs, the broad H α emission has two well-separated peaks, probably indicative of an accretion disk.

1. Introduction

Over 20 years ago, Heckman (1980) described a class of galactic nuclei whose optical spectra are quite distinct from those of both H II regions and classical active galactic nuclei (AGNs). These objects, dubbed “Low-Ionization Nuclear Emission-line Regions” (LINERs), are characterized by narrow emission lines of relatively low ionization. Specifically, membership in this class was defined by only two line-intensity ratios: $[\text{O II}] \lambda 3727 / [\text{O III}] \lambda 5007 \geq 1$, and $[\text{O I}] \lambda 6300 / [\text{O III}] \lambda 5007 \geq 1/3$. Since the exact divisions are somewhat arbitrary, objects formally satisfying only one of the criteria, but nearly consistent with the other, are also commonly called LINERs.

Several authors (e.g., Veilleux & Osterbrock 1987) noticed that unambiguous LINERs, such as NGC 1052, have $[\text{N II}] \lambda 6583 / \text{H}\alpha \gtrsim 0.6$ and $[\text{O III}] \lambda 5007 / \text{H}\beta \lesssim 3$, unlike most H II regions. Kewley et al. (2001) adopted a related scheme using theoretical models. Also, some samples of LINERs in the literature have relied on only the $[\text{O II}] / [\text{O III}]$ ratio; $[\text{O I}]$ was not visible due to low signal-to-noise ratios or insufficient spectral coverage.

Heckman (1980) estimated that $\gtrsim 1/3$ of all spiral galaxies are LINERs, and other surveys of nearby galaxies also showed that LINERs are very common, especially in early-type galaxies (Ho, Filippenko, & Sargent 1997a, and references therein). Given their great preponderance, it is important to determine

whether LINERs are miniature (very low luminosity) QSOs; if so, we should certainly include them in the luminosity function of AGNs.

Although many low-luminosity “AGNs” (in quotes, because we still don’t know their exact physical nature) are LINERs, there are some exceptions, such as the *Seyfert 1* nucleus of NGC 4395 (Filippenko, Ho, & Sargent 1993). Thus, “low luminosity” does not necessarily imply “low ionization.” Also, some luminous “AGNs” are LINERs, especially bright infrared galaxies.

Note that extended (few kpc) “LINER” emission is sometimes seen in galaxies having starbursts, galactic winds, or cooling flows, or in interacting/merging galaxies. These objects are *not* the focus of the current review, although the relevant physical mechanisms will be considered to some extent. Rather, the emphasis here is on LINERs within a radius of 200 pc from the nucleus.

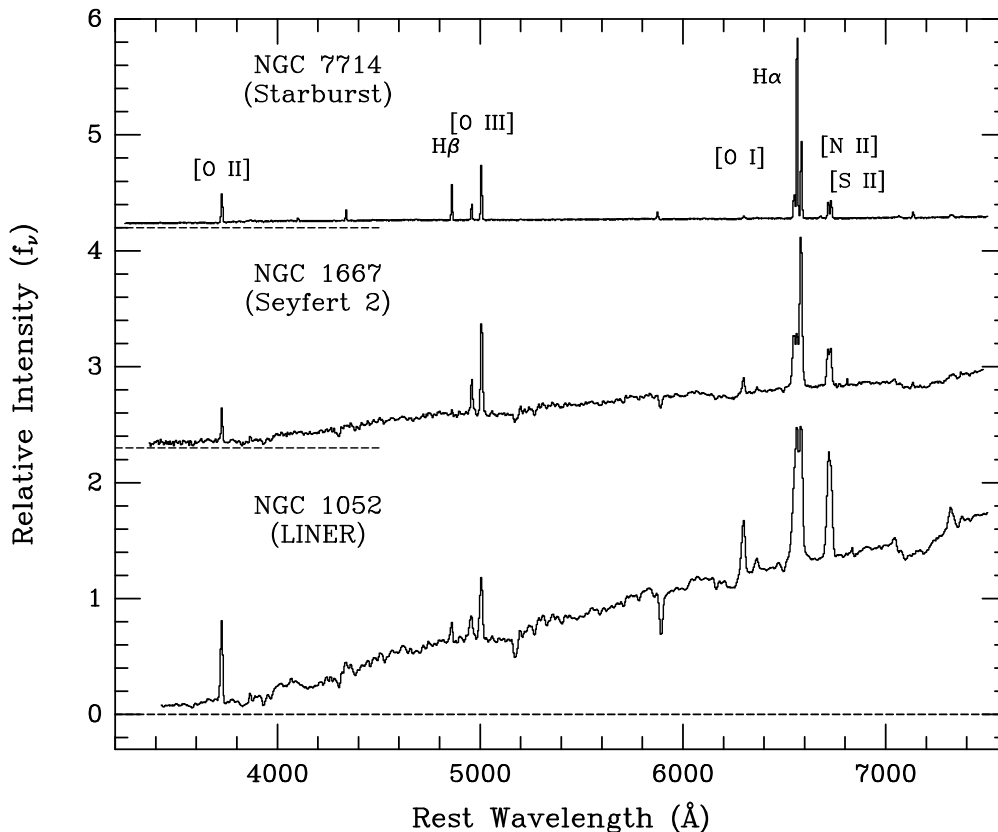


Fig. 1. Spectra of NGC 7714 (a normal starburst galaxy), NGC 1667 (a Seyfert 2 galaxy), and NGC 1052 (a LINER). The relative strengths of the oxygen emission lines are used by Heckman (1980) to define LINERs.

2. The Palomar Observatory Galaxy Survey

An extensive survey of 486 bright, nearby galaxies that my collaborators and I conducted now makes it possible to reassess the demographics of LINERs and

to determine in detail their optical characteristics. The sample consists of all galaxies with $B_T \leq 12.5$ mag and $\delta > 0^\circ$ (Filippenko & Sargent 1985). CCD spectra were obtained with the 5-m Hale reflector at Palomar Observatory over the wavelength ranges 4230–5110 Å and 6210–6860 Å with roughly 4 Å and 2.5 Å resolution, respectively. An atlas of spectra is presented by Ho, Filippenko, & Sargent (1995). Excellent starlight subtraction was achieved through a χ^2 minimization algorithm (Rix & White 1982) involving the large number (~ 60) of absorption-line “template” galaxies in the survey. We were consequently able to measure the relative intensities of most lines to high accuracy (Ho, Filippenko, & Sargent 1997a), permitting detailed comparisons with calculations of excitation mechanisms.

We confirm that LINERs are very common (Ho, Filippenko, & Sargent 1997b), especially among early-type galaxies. An important distinction, however, is that our results are quantitatively more reliable than those of previous surveys, both in a statistical sense and for individual objects. This is due to our combination of small entrance apertures, moderate resolution, high signal-to-noise ratios, and careful starlight subtraction. If we define the LINER category to include both “pure” LINERs and “transition objects” (those with low [O I] $\lambda 6300/\text{H}\alpha$ ratios; they may be LINER/H II composites), then at least 32% of all bright galaxies are LINERs. LINERs are found among $\sim 40\%$ of E, S0, and Sb galaxies, and among 60% of Sa galaxies. For comparison, none of the E–E/S0 galaxies in our sample contain H II nuclei; instead, H II nuclei reside in over 75% of late-type galaxies (Sc and later). If we temporarily assume that all LINERs and transition objects are indeed AGNs, then over 50% of E, S0, and Sb galaxies contain active nuclei; the fraction is closer to 75% for Sa galaxies. Of the complete sample of 486 galaxies in the Palomar survey, 43% are AGNs: 11% Seyfert, 19% LINERs, and 13% transition objects.

3. LINERs: True AGNs or Impostors?

3.1. Photoionization by a Nonstellar Continuum

Based on the spectroscopic resemblance between LINERs and supernova remnants, as well as on high electron temperatures (T_e) derived from the [O III] $\lambda 4363$ /[O III] $\lambda 5007$ intensity ratio, several early studies concluded that the emission lines in LINERs are produced by shock-heated gas (Koski & Osterbrock 1976; Fosbury et al. 1978; Heckman 1980), which may have nothing to do with accretion onto a compact object. In fact, Baldwin, Phillips, & Terlevich (1981) used the line-intensity ratios observed in LINERs to *define* the region populated by “shock-heated galaxies” in their two-dimensional classification schemes (see also Veilleux & Osterbrock 1987).

However, the apparent continuity of LINERs and Seyfert galaxies in the Baldwin et al. (1981) diagrams, together with the discovery of significant X-ray emission in some LINERs, soon led to the development of power-law photoionization models of LINERs (Ferland & Netzer 1983; Halpern & Steiner 1983). In this view, LINERs are genuine AGNs, sustained by whatever mechanism produces the nonstellar UV continuum in QSOs (presumably accretion of matter onto a supermassive black hole), but with a low ionization parameter U (ratio of ionizing photons to nucleons at the face of a gas cloud).

Two problems with this interpretation were that the derived value of T_e was too high in a few objects, and that the entire *set* of emission-line intensity ratios in a given object could be difficult to match with low-density models (e.g., the [O I] $\lambda 6300$ line was sometimes observed to be very strong). The discovery of a wide range of electron densities ($n_e = 10^2$ – 10^7 cm $^{-3}$) in the narrow-line regions of some well-studied LINERs, based on the presence of a strong correlation between line width and critical density for de-excitation, removed or substantially ameliorated these problems (Filippenko & Halpern 1984; Filippenko 1985; Filippenko & Sargent 1988; Ho, Filippenko, & Sargent 1993) — although this is still occasionally overlooked in the literature (e.g., Dopita & Sutherland 1995; Kewley et al. 2001). For example, the value of T_e deduced from the [O III] lines decreases considerably when collisional suppression of the [O III] $\lambda\lambda 4959, 5007$ lines relative to [O III] $\lambda 4363$ is properly taken into account.

Most recently, Barth et al. (2001) analyzed *Hubble Space Telescope* (*HST*) spectra of the LINER NGC 4579 that directly demonstrate the presence of a density gradient within the inner arcsecond of the narrow-line region. The intensity ratio of the narrow [S II] $\lambda\lambda 6716, 6731$ lines exhibits a pronounced gradient, indicating a steep rise in density toward the nucleus. Moreover, the [O I] $\lambda 6300$ /[S II] $\lambda\lambda 6716, 6731$ ratio increases sharply with decreasing distance from the nucleus. There is now no doubt that the narrow-line region is stratified, and that a range of densities must be considered. When this is done, the “high- T_e problem” vanishes; the temperature in the O $^{++}$ zone is comfortably below 20,000 K, and photoionization models work well for compact LINERs.

3.2. Shocks

Shock heating is clearly important in some *extended* LINERs — those involving superwinds, interactions, mergers, and radio jets entraining ambient material. For example, NGC 3079 (Filippenko & Sargent 1992) exhibits ample evidence of shock-excited gas, as do many IRAS galaxies. The relevance of shocks to galactic *nuclei*, on the other hand, is less obvious.

Dopita & Sutherland (1995, 1996) have revitalized interest in shock models of Seyferts and LINERs; the key new insights are that the shock velocities and magnetic field strengths may be very large. High-velocity shocks ($v \approx 200$ – 500 km s $^{-1}$) produce energetic photons capable of ionizing unshocked upstream gas; the resulting emission-line intensity ratios are similar to those observed. Dopita & Sutherland postulate that in Seyfert nuclei, there is plenty of gas to be photoionized, while in LINERs there is a dearth of gas (and hence the high-ionization lines are weak).

High-velocity shocks may well be operating in the circumnuclear region of the LINER M87: *HST* UV/optical spectra of part of the central disk show strong emission lines having relative intensities in good agreement with theoretical predictions (Dopita et al. 1997). However, the UV and optical emission lines in the *exact nucleus* of M87 have intensity ratios that are inconsistent with the predictions of shock models (Sabra et al. 2003; Shields et al., these proceedings). Furthermore, the emission lines in most LINERs and Seyferts have FWHM ≈ 100 – 200 km s $^{-1}$, too slow for the relevant shocks. It is also energetically difficult for shocks to produce the amount of line emission seen in galactic nuclei; the gas must be repeatedly re-energized. The clear presence of a

point-like source of ionizing radiation in some LINERs and Seyfert 2 nuclei, and in most type 1 Seyferts, does not appear to be explained in the current shock models. Finally, as mentioned by Andrew Wilson at this meeting, the *Chandra* X-ray Observatory has not revealed the presence of very hot gas in some key objects such as the Seyfert nucleus of NGC 1068. I conclude that shock heating may be dominant in some nuclear *regions*, but probably not in many galactic *nuclei*. Rather, accretion onto a compact, supermassive black hole is more likely to dominate.

3.3. Cooling Flows

Another alternative is that some LINERs may be cooling accretion flows (e.g., Heckman 1981; Fabian et al. 1986; Heckman et al. 1989), since optical spectra of LINERs closely resemble those of extended gas in some giant elliptical galaxies such as M87. Indeed, cursory inspection of Figure 2a in Shields & Filippenko (1990) shows that the filaments of NGC 1275 (in the Perseus cluster) easily meet the defining characteristics of LINERs. Sabra, Shields, & Filippenko (2000, and references therein) discuss several possible mechanisms to explain the energetics and spectra of the NGC 1275 filaments, but no clear picture has emerged.

Long-slit spectra of some early-type galaxies demonstrate that the emission-line intensity ratios are not very dependent on projected radial distance from the galactic nucleus (Filippenko 1984). This is very difficult to understand in the context of photoionization models, since $U \propto (nr^2)^{-1}$, and the density appears to be independent of radial distance (r) in these objects. It might, however, be consistent with the cooling-flow hypothesis. On the other hand, *most* LINERs are probably not cooling-flow galaxies; we don't see extended emission-line gas of this type.

3.4. Stellar Photoionization

Hot, evolved, low-mass stars (post-asymptotic giant branch stars) might provide sufficient ionizing photons to produce the weak, extended [N II] (LINER-like) emission lines observed in some galaxies (Binette et al. 1994; Taniguchi, Shioya, & Murayama 2000). However, this is probably not applicable to most *compact* LINERs.

The “Warmer” hypothesis of Terlevich & Melnick (1985) has received much attention in the past, and it may be relevant in a few galactic nuclei classified as Seyferts and LINERs. However, *HST* spectra of Seyferts and LINERs don't reveal the presence of Wolf-Rayet stars in almost all cases (e.g., Barth et al., these proceedings). A less extreme variant of this model is that O-star photoionization powers some LINERs, especially the transition objects (Filippenko & Terlevich 1992) and galactic nuclei having high electron densities (Shields 1992). Motivated by the UV spectrum of the LINER NGC 4569, which clearly reveals a recent starburst, extensive stellar photoionization models involving realistic star clusters have been explored by Barth & Shields (2000).

Very recently, Ho, Filippenko, & Sargent (2003) tested the stellar photoionization hypotheses by examining the stellar continua and absorption lines in their Palomar survey of nearby galactic nuclei. They find that LINERs and Seyferts generally have *old* stellar populations; there is no clear evidence for young stars. This applies even to LINER/H II transition objects, although enhanced star

formation is sometimes visible. Similarly, Barth et al. (these proceedings) examined *HST* STIS spectra of 13 transition objects and generally found an old stellar population. While some of the objects are true LINERs on very small angular scales, others retain their “transition” classification. These data do not firmly support the stellar photoionization hypothesis in compact galactic nuclei; however, *extended* starbursts and super-starbursts are clearly relevant in many IRAS galaxies and similar objects (e.g., Kewley et al. 2001).

4. Tests of the AGN Hypothesis

As discussed above, there is now much circumstantial evidence that many (though not all) compact LINERs are powered by accretion, as are QSOs and genuine AGNs. The discovery that supermassive black holes are present in the nuclei of a majority of massive, nearby galaxies (e.g., Gebhardt et al. 2000) is consistent with this conclusion. Ironically, owing to an observational selection bias, the galaxies having the best existing dynamical evidence for supermassive black holes tend to be LINERs and low-luminosity AGNs whose spectra are *not* dominated by emission lines. But there are other, independent tests of the AGN hypothesis for LINERs, as discussed below.

4.1. Broad H α Emission

An important aspect of our Palomar survey is the search for broad H α emission similar to, but weaker than that found in classical type 1 Seyferts and QSOs. Indeed, one of our main goals is to quantify the luminosity function of broad-lined AGNs. Identification of broad H α emission in LINERs (“LINER 1s”) is especially significant, as these objects then become prime candidates for genuine AGNs. [Before continuing, I note that some authors (e.g., Krolik 1999) incorrectly state that LINERs having broad permitted emission lines should be called Seyfert galaxies. Actually, however, the LINER/Seyfert classification is based on the intensity ratios of the *narrow* components of emission lines. The presence or absence of broader permitted lines is used to subclassify an object as “type 1” and “type 2,” respectively.]

Our search technique and conclusions are described in detail by Ho et al. (1997c). We find that 24% of “pure” LINERs contain broad H α emission — a lower limit to the true fraction of LINER 1s, since the feature may sometimes be below our level of detectability. Very few (about 4%) of the transition objects exhibit broad H α emission. The Hubble types of the galaxies are Sbc and earlier, and the fraction is highest among E–E/S0 LINERs. Type 1 AGNs are found in 9.5% of the Palomar galaxies; they constitute 22% of all AGNs (16% of all LINERs including transition, and 37% of all Seyferts). In the *HST* STIS survey of transition objects by Barth et al. (these proceedings), 1 new broad-lined object was found among the 13 observed galaxies.

It is possible that the “unified model” for Seyfert galaxies (Antonucci 1993), in which a majority of type 2 Seyferts are obscured Seyfert 1s, also extends to LINERs. To test this hypothesis, we have used the Keck 10-m telescope to conduct a spectropolarimetric survey of low-luminosity AGNs (LINERs and low-luminosity Seyferts). We uncovered the first known examples of hidden broad-line regions in LINERs (including the prototypical LINER, NGC 1052),

demonstrating that at least some of these objects are genuine AGNs surrounded by obscuring tori, analogous to the torus model for Seyfert nuclei and high-power radio galaxies (Barth et al. 1999a,b).

4.2. The Nonstellar Continuum

Another way to test the AGN hypothesis is to search for a point-like nonstellar continuum in LINERs. Since the optical continuum of LINERs is generally dominated by old, red stars, this is much more easily done at UV wavelengths. The surveys by Maoz et al. (1995) and Barth et al. (1998) revealed that only $\sim 25\%$ of LINERs harbor a compact source of UV emission. Dust probably blocks the nucleus in many cases, as suggested by the fact that the average galaxy disk inclinations of “UV-bright” and “UV-dark” nuclei are 36° and 63° , respectively. The fraction of intrinsically UV-bright LINERs may therefore be closer to 50%. However, to determine the physical nature of the UV source, spectra are needed.

The first high-quality *HST* UV spectrum of a LINER was that of M81 (Ho, Filippenko, & Sargent 1996). It exhibits broad permitted emission lines, further reinforcing the similarity to Seyfert 1 nuclei. A featureless continuum, most likely of nonstellar origin, is detected unambiguously for the first time in M81. A UV spectrum of the LINER 1 NGC 4579 is similar to that of M81 (Barth et al. 1996), and several other LINER 1s also broadly resemble Seyfert 1s in the UV. On the other hand, some LINER 2s exhibit evidence for young starbursts (e.g., NGC 4569; Maoz et al. 1998), while the data for others are still ambiguous.

Perhaps the clearest signature thus far for AGNs in many LINERs is provided by X-ray images (e.g., Roberts & Warwick 2000; Halderson et al. 2001). The most recent evidence is the most compelling: an unresolved hard X-ray core is found in 75% of the 24 galaxies in the high-resolution *Chandra* HRI survey of Ho et al. (2001), including all LINER 1s, most LINER 2s, and a few transition objects. This strongly suggests that LINER 1s and most LINER 2s are genuine AGNs. In addition, ASCA measurements show that the X-ray luminosity is proportional to the $H\alpha$ luminosity (Terashima, Ho, & Ptak 2000), as previously found for more luminous AGNs.

Additional strong evidence for nonstellar processes in LINERs comes from radio imaging surveys (e.g., Nagar et al. 2000; Filho, Barthel, & Ho 2000, 2002): 64% of LINER 1s and 36% of LINER 2s have compact radio cores. Ho et al. (2003, in prep.) show that 80% of LINERs have a flat-spectrum radio core, with LINER 1s outnumbering LINER 2s in this regard. Only 25% of transition objects have such a core, while 0% of H II galaxies exhibit one. Complementing these results, the VLBI measurements of some LINER 1s give brightness temperatures exceeding 10^8 K (Falcke et al. 2000), a clear sign of nonstellar activity.

5. Double-Peaked Broad $H\alpha$ Emission

Quite a few LINERs exhibit very broad, double-peaked $H\alpha$ emission. The prototypical case is that of Arp 102B (Halpern et al. 1996, and references therein; Ho et al. 2000; Shields et al. 2000). It has been shown by Eracleous & Halpern (1994) that AGNs exhibiting such profiles also distinguish themselves in several

other respects. Specifically, nearly all of them are radio loud, and they tend to (a) be dominated by a stellar continuum at optical wavelengths, (b) have Balmer lines which are about twice as broad as those of typical radio-loud AGNs, and (c) have unusually strong, low-ionization forbidden lines whose intensity ratios are reminiscent of those of LINERs. Additional possible properties may include a flat far-infrared spectrum and a weak UV continuum, with little evidence for the “big blue bump.”

Halpern and collaborators have considered in some detail the possibility that the line profiles are produced by an accretion disk (Chen, Halpern, & Filippenko 1989; Eracleous & Halpern 1994). The *HST* spectra of Arp 102B presented by Halpern et al. (1996) strongly support the application of the accretion disk model of Dumont & Collin-Souffrin (1990a,b,c), in which the disk produces only low-ionization lines. Moreover, the work of Ho, Filippenko, & Sargent (1996), Ho (1999, and these proceedings), and others suggests that low-luminosity AGNs accreting at low rates relative to the Eddington rate have geometrically thick, ion-supported inner tori, providing a natural explanation for many of the observed properties of double-peaked AGNs.

6. Conclusions

I summarize this review by providing a “score card” for galactic nuclei. The first trait is the presence of a supermassive black hole. By examining lists of specific objects in papers having dynamical mass estimates, I conclude that such an object exists in most or all LINER 1s, and usually in LINER 2s as well. It is sometimes (often?) present in transition objects, and perhaps rarely in H II nuclei, although definitive conclusions cannot yet be made because there are too few good measurements of late-type galaxies (the most common H II and transition objects). The second trait, broad $H\alpha$ emission, is present in all LINER 1s (by definition!), some LINER 2s (in polarized flux, but occasionally barely visible in total flux as well), rarely in transition objects, and never in H II nuclei. Third, a point source emitting a nonstellar continuum (UV, X-ray, radio) is almost always present in LINER 1s, often (usually?) in LINER 2s, rarely in transition objects, and never in H II nuclei. Fourth, the stellar population is nearly always old in LINER 1s and LINER 2s, usually old (but sometimes young) in transition objects, and always young in H II nuclei. Fifth, the narrow-line gas is photoionized by a nonstellar continuum in all LINER 1s and most LINER 2s, while gas in transition nuclei can be photoionized by nonstellar or (sometimes) stellar continua, and H II nuclei are photoionized by hot stars.

From these observed characteristics, I conclude that LINER 1s are always, or almost always, genuine AGNs. Similarly, LINER 2s are often (perhaps usually) genuine AGNs. Transition objects are a mixture of AGNs and other processes (generally starbursts?); in some cases they may be hidden AGNs that will be revealed by more detailed searches. H II nuclei are powered by starbursts, regardless of whether a central black hole is present. These conclusions apply to compact nuclei, not to extended regions whose emission lines are produced by shocks, superwinds, and cooling flows.

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